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Hydraulics of lamella sedimentation.

A study of the lamella settlers at Ringsjö water treatment plant, Sweden.

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Abstract

This study investigates the lamella settlers in Ringsjö water treatment plant, Sweden, in terms of water movement and performance. The treatment plant has two blocks with differences in the flocculation and lamella settlers, where block 1 is not able to process the maximum designed flow rate without the addition of polymers. Through data analysis the problem was confirmed, showing that the two designs have the same turbidity when block 1 has approximately 20 % less flow rate than block 2. Moreover, variables such as settling velocity and turbidity were measured and used to estimate and evaluate the removal rate of the system, while the hydraulic losses of the system appear to be negligible in both lamella designs. Three future possible designs of the settlers that could increase their capacity were investigated but as the cause of the problem remains unclear, which design would be more efficient is uncertain. However, as the problem started when the coagulant was changed and currently the capacity of block 1 is increased with the use of a polymer, the possibility that the flocculation plays an important role in the cause of the problem is discussed, and it is concluded that there is a need to further investigate the floc characteristics.

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1. Introduction

1.1. Background

Sydvatten AB produces about 75 million m^3 of drinking water each year, serving around 900 000 inhabitants in southern Sweden through two water treatment plants, Vomb and Ringsjö water treatment plant, located next to the lakes Vombsjön and Ringsjön, respectively. Ringsjö water treatment plant is supplied with water from Lake Bolmen through an 80-km long tunnel, and the purification procedure consists of coagulation/flocculation followed by lamella settlers as a separation step, rapid and slow sandfilters, UV disinfection and finally a low dose of hypochlorite. This procedure takes place in 2 blocks with 4 lines each, with a nominal design flow of 2400 l/s, but a 1400 l/s yearly average production of drinking water, i.e. 700 l/s per block.

When the treatment plant started its operation there was one block of production, block 1, including lines 1-4. At that time, the source of raw water for the treatment plant was lake Ringsjön and aluminium sulphate ($Al_2(SO_4)_3$) was used as coagulant. Due to predictions that the water demand would be increased, it was suggested that Lake Bolmen would be a source of water with the potential to satisfy higher demands and after the construction of the Bolmen tunnel in 1976-1987, Lake Bolmen became the new source of water for the treatment plant. Some years later the coagulant was changed to Ferric Chloride ($FeCl_3$) in block 2 when it was taken into operation in 1997. Block 2 has four additional lines, lines 5-8.Ferric chloride was introduced in block 1 during 1999- 2000 and since 2000, the two blocks follow the same purification procedure as mentioned above, with identical rapid and slow sandfilters but different flocculation and sedimentation basins in terms of volume and design. The two blocks are designed to process the same maximum flow but in reality, block 1 does not respond well under such a high flow. At the moment, a polymer is occasionally added to the flocculation basins making it possible for block 1 to achieve a good performance under higher flow rates.

Due to expectations of higher water demand in the future, it is of interest to increase the capacity in block 1, so that it will be able to process higher flow rates, without the aid of polymers. In the past, investigations of the problem were made suggesting that changes in the inlet's structure could increase the settlers' capacity. These changes were made in Line 3 but the result was not satisfactory. Currently there are 3 different designs of lamella settlers in Ringsjö water treatment plant. Lines 1, 2 and 4 are using a pyramid shape basin with the same structure as when the treatment plant started to operate. Line 3 has the same shape of basin but a different inlet structure. Lines 5-8 have a rectangular shape basin with completely different inlet structure than lines 1-4. In this study the hydraulics of Ringsjö water treatment plant's lamella settlers will be investigated and evaluated. Furthermore, possible modifications in the basins' design to increase the capacity in block 1 will be simulated and evaluated.

1.2. Objectives

The main aim of the study is to investigate the design of the lamella basins in the different blocks with regards to water movement and removal efficiency, making it possible to evaluate the present and future, improved designs. The causes for the different behaviors between the two blocks will be studied.
The detailed objectives are:

- Create a hydraulic model of the lamella basin to simulate the flow and removal rate of the basins and validate it with existing and newly collected data.
- Consider possible modifications of the current system and investigate how they would affect the capacity of the system.

1.3. Procedure

The study begins with a literature review about lamella sedimentation with focus on the hydraulic conditions, including the removal rate of such basins. The lamella basins at Ringsjö water treatment plant were investigated based on available drawings and data regarding daily values of turbidity (at the outlet of the basins), flow, temperature and dosage of coagulant (during the chemical precipitation) that are continuously measured by the treatment plant. In addition, turbidity measurements at different locations along the basin, and sedimentation tests were carried out for a better understanding of the system behavior. After all the necessary information was collected and analyzed, a hydraulic model was developed representing the flow conditions and sediment removal, in order to evaluate the current design. Furthermore, possible future designs that might improve the capacity are considered and analyzed. Finally, the behavior of the system and how the differences between the two blocks can lead to some indications about the problem's causes are discussed.

1.4. Problem statement and limitations

Ringsjö water treatment plant is designed for a maximum water production of 2400 l/s, meaning each block has a design capacity of 1200 l/s, without the use of polymers. However, block 1 has a de facto capacity of 900 l/s instead of 1200 l/s resulting in about 21% reduction of the maximum possible production of drinking water. The problem is located in the separation step, as for a high flow rate, the turbidity of the water leaving the lamella settlers is significantly high, higher than the values of turbidity that are registered in block 2. The difference in design of the blocks is the main reason why they respond differently under high flow rate.

One important limiting factor of this study was the lack of knowledge on floc characteristics in the chemical precipitation and thus actual settling velocity of the suspended matter in the lamella settlers cannot be estimated. Though sedimentation tests were conducted, polymers were used in lines 1-4, so the results do not represent how the lines function without the addition of polymers. On the other hand, even though drawings of the basins were studied, details regarding the structure and geometry of the inlet channels in block 1 were not very clear, while reports suggest that in line 3 the inlet channels have been reconstructed but there are no drawings of these changes. However, under a period that line 3 was temporally shut down and the basins were emptied, line 3 was inspected and the current design of the line is now known. The other lines are assumed to have the same design as the one appears in the drawings.

2. Treatment plant

In this chapter, the purification process and the designs of the lamella settlers in Ringsjö water treatment plant are presented. The two blocks of the treatment plant are compared and their differences regarding the flocculation and sedimentation basins are discussed in detail. Furthermore, the current operational problems of the lamella sedimentation are discussed.

2.1. Purification process

Ringsjö water treatment plant produces on average 1400 liters of water per second every year, which is distributed in several municipalities in Skåne. The water is extracted from lake Bolmen through an 80 km long tunnel and afterwards it is transported a final stretch through a 25 km long pipe to the treatment plant. The purification procedure consists of the following stages in two blocks with 4 lines of production each (Figure 2.1):

- *Coagulation, flocculation and sedimentation*. Ferric chloride ($FeCl_3$) is added to the water in order to create flocs together with the organic matter present in the raw water in the flocculation basins. Flocculation is followed by lamella sedimentation where the flocs will settle at the bottom to be removed.
- *Sandfiltration.* To remove the remaining flocs, the water is filtered through a rapid sandfilter and up next the water enters a slow sandfilter, where odour and taste as well as microorganisms are removed.
- *UV light and disinfection.* The water is illuminated with short-wave ultraviolet light to disinfect the water by preventing some pathogens to reproduce. After the UV light a small dose of hypochlorite is added in the water.

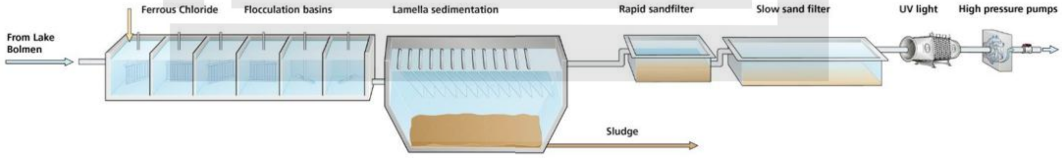


Figure 2.1: Ringsjö water treatment plant's purification process (Sydvatten AB, 2018).

2.2. Lamella settlers

As stated above flocculation is followed by a separation step that consists of lamella sedimentation settlers. Though both blocks follow the same purification procedure and are designed to produce the same quantity of drinking water, the volume of their flocculation basins and the design of lamella settlers differ. As far as the flocculation basins are concerned, their volume in block 2 is larger, resulting in higher detention time which is an important parameter for the floc growth (table 2.1).

Table 2.2.1: Difference of flocculation and sedimentation basins between block 1 and 2.

Flocculation basins	
Block 1	Block 2
Number of basins : 6	Number of basins : 6
Total volume : 3200 m^3	Total volume : 3940 m^3
Residence time of 1200 l/s : 45 min	Residence time of 1200 l/s : 55 min
Lamella sedimentation	
Block 1	Block 2
Number of basins: 8	Number of basins: 4
Number of lamella rows per basin: 4	Number of lamella rows per basin: 8
Dimensions of lamella plates: 1,16x2,55 m	Dimensions of lamella plates: 1,25x2,37 m
Number of lamella plates per row : 120 Total number of lamella plates: 3840	Number of lamella plates per row : 110 Total number of lamella plates: 3520
Lamella area : 6300 m^2	Lamella area : 5800 m^2
Inclination angle : 55°	Inclination angle : 55°
Horizontal distance between plates : 10 cm	Horizontal distance between plates : 10 cm
Volume of basin : 3280 m^3	Volume of basin : 7850 m^3

On the other hand, the lamella sedimentation of the two blocks have significant different designs. Block 1 use lamella settlers with a pyramid shape under the lamella packs, while block 2 is using settlers with rectangular shape (figure 2.2), while the volume of sedimentation basins in block one is approximately 59% smaller than block 2 (table 2.1). Though each line in each block uses eight rows of lamella plates, block 1 has two basins per line (with 4 rows each) and block 2 one basin per line (Appendix A, fig. A.1 and A.2).

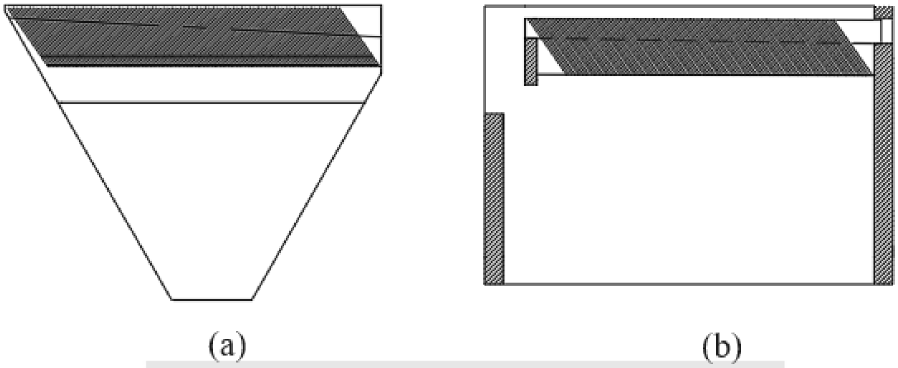


Figure 2.2: Cross section of lamella basin in a) Block 1 and b) block 2.

Moreover the size of lamella plates and the number of plates used in each block differs but they are placed with an angle of 55º and 10 cm horizontal distance in both blocks (table 2.1). In addition, lamella settlers in each block have a different inlet design. In block 1, the inlet structure is more complicated, as the water is distributed between the lamella plates from their side (left and right), through distribution channels (figure 2.3), while in block 2 it is entering underneath the lamella plates' row. In that case there is no inlet channel. The water is simply flowing under the lamella row and it is distributed equally between the lamella plates.

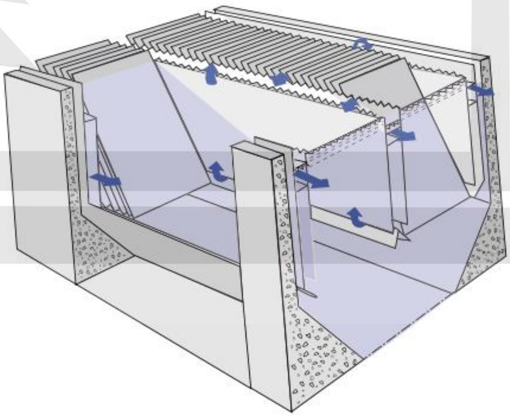


Figure 2.3: Lamella sedimentation basin with a similar design as in Block 1(Svenskt Vatten AB, 2007).

The main reason why the two blocks have those differences is that the blocks were not build for the same type of raw water. Block 2 was built much later than block 1, when raw water was supplied by lake Bolmen to the treatment plant and thus it was designed to process lake Bolmen's water while block 1 was designed to process lake Ringjön's water originally. The difference in the quality of raw water between these two lakes lies to the fact that Lake Ringsjön is more affected by the population around it since it is located in a place with agriculture activity and the phenomenon of eutrophication has been noticed together with high concentrations of phosphorus while lake Bolmen was not affected by such activities resulting in having a better quality of water. Today Lake Ringsjön is considered to be a backup source of water that would be used in case something prevents water from Lake Bolmen to reach the treatment plant.

2.3. Operational problems

As mentioned earlier, the lines of block 1 cannot operate well under high flow rates, resulting in reduction of the maximum possible production of the treatment plant, if polymers are not added in the block. The problem is probably due to the escape of sedimented sludge at the bottom of the sedimentation basins when the flow is high but could also be because of the inlet design to the basins in block 1. The problem is more severe during seasons with low temperatures, as temperature is a factor that affects the formation of the flocs and under low temperatures smaller flocs are created (Fitzpatrick, Fradin, & Gregory, 2004). This problem appeared in block 1, after the coagulant was shifted from aluminium sulphate ($Al_2(SO_4)_3$) to Ferric Chloride ($FeCl_3$). In general, sedimentation with lamella plates is considered a process sensitive to operation shifts as this settlers have small retention times and changes in raw-water quality and other disturbances to the process can affect significantly the sedimentation rate (Binnie & Kimber, 2013).

3. Theory of lamella sedimentation

3.1. Lamella sedimentation with the Hazen model

Sedimentation in a lamella settler is based on Hazen's load theory (1904), according to which, it is assumed that the smallest particle to be removed is the one that can settle during its horizontal transport through the basin. Thus, for a horizontal basin of rectangular shape with length l and water depth h, the smallest particle that will have time to settle is determined by the fall speed (w_c),

$$w_c = V\frac{h}{l} \tag{1}$$

Where, V is the horizontal velocity through the basin.

If the same theory is employed for a lamella settler, the angle of the lamellas (α) enters into the problem. As a particle travels along the lamellas, the time for it to settle on the lower lamella is $h/w_c\cos\alpha$, whereas the time it takes for the particle to move through the lamellas is $L/(V-w_c\sin\alpha)$. Thus, the smallest particle that can be removed by the lamella settler is determined by the fall speed:

$$w_c = \frac{hV}{L\cos\alpha + h\sin\alpha} \tag{2}$$

If $\alpha = 0$, then Eq. 2 reduces to Eq. 1, whereas for $\alpha = 90^{\circ}$ $w_c = V$, that is, the settling velocity has to be larger than the water velocity through the lamellas in order for sedimentation to occur.

In the case that the settling velocity (w) is smaller than the critical velocity given by Eq. 2, then only a certain ratio of the incoming particles will be removed. Assuming well-mixed conditions at the inflow section to the lamellas, a particle settling at w will reach the lower lamella at L, if suspended at an elevation s in the inflow section,

$$s = \frac{Lw\cos\alpha}{V - w\sin\alpha} \tag{3}$$

Where $w \leq w_c$ and $0 \leq s \leq h$. All particles suspended above s will pass through the lamellas without settling. Thus, the ratio of particles removed (β) is obtained as:

$$\beta = \frac{s}{h} = \frac{cos\alpha}{V/w - sin\alpha}\frac{L}{h} \tag{4}$$

If the critical settling velocity given by Eq. 2 is introduced, then Eq. 4 may be expressed as:

$$\beta = \frac{w}{w_c}\frac{V/w_c - sin\alpha}{V/w_c - w/w_c - sin\alpha} \tag{5}$$

For the case of a horizontal basin (α = 0), $\beta = w/w_c$; also, if $w = w_c$ then β = 1. The total mass transport to a pair of lamellas is given by $\dot{m_o} = c_o VBh$, where c_o is the concentration of particles in the incoming water to the lamellas and B the width of a lamella. If $w < w_c$, then all the sediment that is transported to the lamellas below elevation s, obtained as $\dot{m} = c_o VBs$, will be removed. Thus, the rate of particle removal is $\beta = s/h = \dot{m}/\dot{m}_o$, so the β expresses the mass of particles that settles along the lower lamella.

3.2. Lamella sedimentation with the advection-diffusion equation

The sedimentation in a lamella settler can also be described by the advection-diffusion equation (ADE). For one-dimensional, unsteady flow, the ADE including advection, diffusion, and sedimentation is written,

$$\frac{\partial c}{\partial t} + V\frac{\partial c}{\partial \chi} = D\frac{\partial^2 c}{\partial \chi^2} - \frac{w}{h}c \tag{6}$$

Where, c is the mean concentration, V the horizontal mean velocity, D the diffusion (or dispersion) coefficient, w the settling velocity, h the water depth, x a spatial coordinate, and t time. Looking at steady-state conditions and neglecting diffusion, taking the x-axis to be in the lamella direction, which is oriented an angle α to the horizontal, result in the following ADE:

$$(V - wsin\alpha)\frac{dc}{d\chi} = -\frac{wcos\alpha}{h}c \qquad (7)$$

The solution to Eq. 7 with the boundary condition that $c = c_{in}$ for $x = 0$ yields:

$$c = c_{in}\exp\left(-\frac{wcos\alpha}{V - wsin\alpha}\frac{\chi}{h}\right) \qquad (8)$$

The amount of sediment that is transported out from the lamella is obtained from:

$$\dot{m}_{out} = c_{out}(V - wsin\alpha)hB \qquad (9)$$

where c_{out} is the concentration at the outflow from the lamellas (*i.e.*, $x = L$) and B the width of the lamellas. Thus, the ratio of the incoming sediment (β) that is deposited along a lamella may be determined from:

$$\beta = \frac{m_{in} - \dot{m}_{out}}{\dot{m}_{in}} = \frac{c_{in} - c_{out}}{c_{in}} = 1 - \frac{c_{out}}{c_{in}} \qquad (10)$$

Employing Eq. 8 in Eq. 9 results in:

$$\beta = 1 - \exp\left(-\frac{wcos\alpha}{V - wcos\alpha}\frac{L}{h}\right) \qquad (11)$$

If the lamella becomes very long, that is, in the limit $L \rightarrow \infty$, then $\beta \rightarrow 1$. Also, if $wsin\alpha \geq V$ no sediment is transported through the lamellas and Eq. 3 is not valid.

On the other hand, Okoth *et al.*(2008), proposed a description of the critical fluid-suspension-sediment interactions with a 3D advection diffusion equation including concentration dependent particle settling velocity in the vertical advection.

$$\frac{\partial C}{\partial t} + \frac{\partial V_\chi}{\partial \chi} + \frac{\partial V_y C}{\partial y} + \frac{\partial (V_z + W_s)C}{\partial z} = \frac{\partial}{\partial \chi}\left(\varepsilon_\chi \frac{\partial C}{\partial \chi}\right) + \frac{\partial}{\partial y}\left(\varepsilon_y \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(\varepsilon_z \frac{\partial C}{\partial z}\right) \qquad (12)$$

Where ε_χ, ε_y, ε_z are sediment diffusion coefficient and V_χ, V_y, V_z are the velocity components in χ, y and z directions.

3.3. Flow between two parallel plates

The flow between the plates in a lamella settler is typically laminar and may be described by the Navier-Stokes equations. For this particular case, an analytical solution is available given by Schlichting (1979):

$$u(y) = -\frac{1}{2\mu}\frac{dp}{d\chi}(b^2 - y^2) \tag{13}$$

Where u is the horizontal velocity, which is constant in the stream-wise direction (x) but varies between the plate (y), μ the dynamic viscosity, dp/dx the pressure gradient (constant; also $dp/dx < 0$, that is, the pressure decreases in the flow direction), b half the distance between the plates, and where the coordinate y originates halfway between the plates. The flow per unit width (q) may be obtained by integrating Eq. 13 over the distance between the plates yielding:

$$q = -\frac{2}{3\mu}\frac{dp}{d\chi}b^3 \tag{14}$$

The mean velocity is derived by dividing the flow q with the distance between the plates d (=2b):

$$\bar{u} = -\frac{1}{12\mu}\frac{dp}{d\chi}h^2 \tag{15}$$

The pressure drop, expressed through the gradient, may be related to the energy loss from friction against the plates (h_L) according to,

$$\frac{h_L}{L} = -\frac{1}{\rho g}\frac{dp}{d\chi} \tag{16}$$

Where L is the length of the plates, g the acceleration due to gravity, and ρ the density of water. In case of inclined plates, the gradient in pressure level should be employed in Eq. 16 that includes differences in elevation. Combining Eq. 14 and 15 gives:

$$h_L = \frac{12\mu}{\rho g h}L\bar{u} \tag{17}$$

From this expression the energy loss between the lamella plates can be estimated.

4. Literature review

A variety of literature can be found about inclined plate settlers as they are widely used in water and wastewater treatment. They are often preferred over the conventional settlers as they decrease the footprint of settling tanks while maximise settling efficiency and have low operational and overall costs. Below different aspects of lamella sedimentation such as design, efficiency and problems are described based on the available literature.

4.1. Lamella settler design and functioning

Lamella sedimentation is based on the Hazen's surface loading theory, according to which, it is not the tank's depth, but the surface that determines the result of the sedimentation process. To extend the surface area in a sedimentation tank, a number of parallel plates or tubes are employed and placed closely at an inclination angle. If the plates or tubes where oriented in a horizontal direction, they would be filled with solids, resulting in increasing the head loss and velocities to a point that the suspended solids would re-enter the water moving upwards. The inclination of the settling surfaces should be to a degree that allows the suspended matter to slide onto them and move towards the sludge zone. On the other hand, both parallel plate and tube settlers have a small detention time, typically less than 20 minutes, but their efficiency rate can be comparable to that of a rectangular settling tank with a minimum detention time of 2 hours (Crittenden, Rhodes Trussell, Hand, Howe, & Tchobaoglous, 2012). In water treatment lamella plate systems are more common, as they are easier to clean and are considered more flexible when it comes to optimization. However, in principle there is no difference between tube and plate systems (Binnie & Kimber, 2013).

Laminar and stable flow conditions are crucial for the operation of inclined plate settling, which are defined by Reynolds and Froude numbers[1] such as $\mathrm{Re} \leq 500$ and $\mathrm{Fr} > 10^{-5}$, according to Fischerström (1955).

Horvath (1994) added that the usual ranges used in conventional settling facilities are: $10^3 < Re < 2.5 \times 10^4$ and $10^{-6} < Fr < 2.6 \times 10^{-5}$, and explained that by increasing inflow (and thus velocity), Froude number changes favorably whereas Reynolds numbers changes unfavorably and discuss how a decrease of the hydraulic radius (R) can also act favorably.

[1] Re= $\frac{uR}{\nu}$ and Fr =$\frac{u^2}{gR}$, where u is the fluid velocity (m/s), R the hydraulic radius (m), ν the kinetic viscosity (m^2/s) and g acceleration of gravity (m^2/s).

As seen in figure 4.1, lamella settlers can be designed to operate under the following patterns (Davis, 2010; Nordic water, 2014; Tarpagkou & Pantokratoras, 2014; Zioło, 1996):

- Counter-current; water and sludge flow have opposite directions.
- Co-current; water and sludge have the same direction (downwards).
- Cross-current; Sludge flow is perpendicular to the water direction.

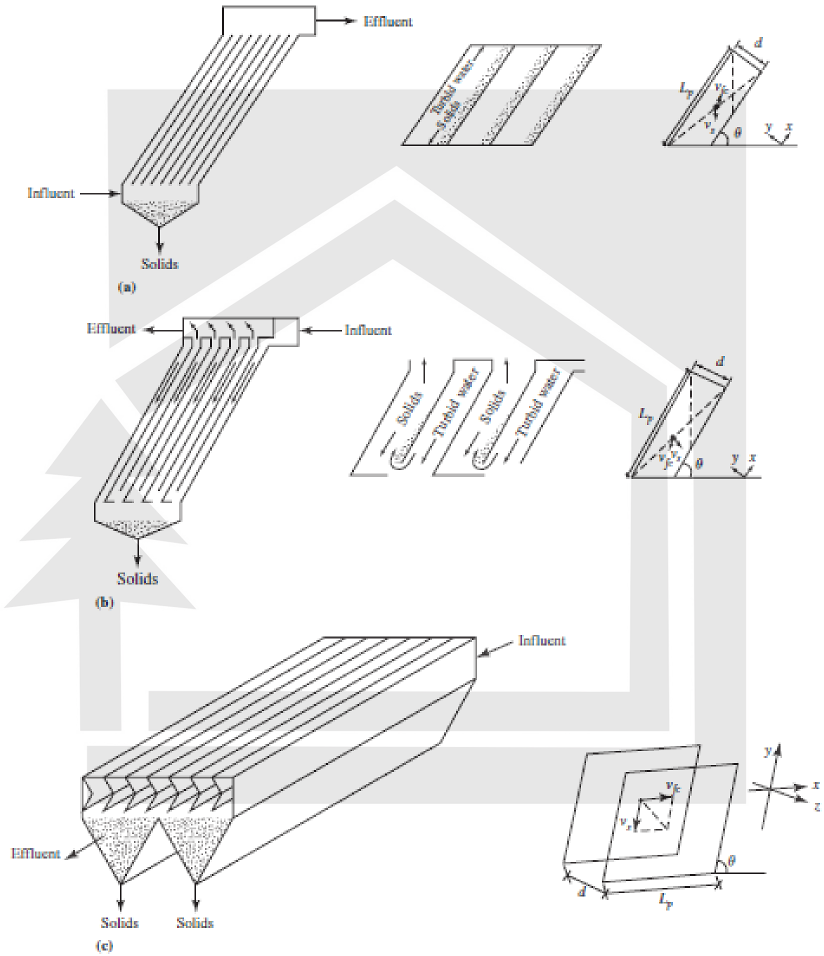


Figure 4.1: Flow patterns for inclined settling systems (a) countercurrent, (b) cocurrent, and (c) crosscurrent (Davis, 2010).

Forsell and Hedström (1975), discussed the important factors that should be considered when choosing a flow pattern for sedimentation and mentioned that, in practice, co-current design is applicable in cases when sludge volume is a small percentage of the feed, while for handling suspensions with large sludge volume fractions counter-current design principle is more suitable. However, counter-current design is preferred due to its simpler design.

Kowalski and Mięso (2003), also mentioned that counter-current flow pattern is preferred, but focused their study on the cross-current flow pattern which is more efficient according to earlier studies. They simulated a mathematical cross-current sedimentation process model and concluded that both the overflow rate and the density of the particles can have a significant influence on the sedimentation.

Tarpagkou and Pantokratoras mention that unstable flow patterns and mixing currents are practically eliminated when the flow is directed to the settling zone through inclined plates or tubes. They examined the process efficiency for both a conventional sedimentation basin and a lamella settler and the results showed that lamella settlers increased the sedimentation efficiency by 20%. In addition, Sarkar et. al. (2007), stated that sedimentation occurs more rapidly in lamella settlers than conventional settlers.

Zioło (1996) stated that a lamella settler's geometry is described by the distance between the plates (d), the length (l) and width (b) of the lamella plates and the angle of inclination (α). By applying and comparing 5 different methods of plate settlers' calculations(for counter-current flow) he suggested that the calculations of the sedimentation efficiency are an implicit function of the relative length (l/b) and inclination angle (α), as sedimentation effectiveness increases with the increase of the relative plate length and the latter decreases as inclination angle increases.

4.2. Lamella settler operation- Experiences and problems

A common drawback of the lamella sedimentation settlers is their low detention time. Forsell & Hedström (1975) explain that the typical detention time in a lamella settler is much shorter than the one of a conventional settler resulting to a low floc growth in the separation stage. This is also one of the reasons why lamella settlers are often used as separation step after coagulation/flocculation. Another problem they address is the risk of clogging which can lead to important operational disturbances in the sedimentation process. However, clogging risk is very low in surface water treatment.

Poh (1984) mentions that laminar conditions are necessary for the settlers function. If turbulent conditions occur, particles are swept upwards by the turbulent current, resulting in re-entrainment of the particles into the suspension fluid and contribute to a poor performance of the settler. Moreover if flow is not equally distributed between the lamella plates, a bypass situation, where some parts of the settler are overloaded and others under-loaded can occur.

Okoth *et al.*(2008), pointed out that due to a poor hydrodynamic design regarding feed distribution, lamella settlers are often characterized by relatively poor performance. The configuration of the inlet of the lamella settlers is often an important parameter affecting the distribution of the suspendered liquid and thus the effectiveness of the settler.

Adelman *et al.*, (2013), investigate the failure mode “floc roll up” for inclined plates. The term floc roll refers to when the settling velocity of a floc along the inclined surface is less than the upward velocity of the fluid at the center of the floc, preventing the flocs from sliding onto the inclined plates for a counter-current flow. Since the velocity gradient is increasing when the space between the plates is decreasing the minimum space between 2 plates (or diameter in case of tubes), is determined based on this failure mode. In the end they showed that under some conditions, inclined settlers can operate even when the minimum space between the inclined surfaces is less than the typical 5 cm.

5. Data compilation and analysis

In this chapter, all the data used in this study; data given by the treatment plant and measured data are presented. The measured data are briefly evaluated based on treatment plant's data during the day the measurements were conducted and parameters such as the concentration of suspended solids in the influent of the lamella settlers and the settling velocity of the flocs. Furthermore, a data analysis is conducted regarding flow rate, turbidity, and water temperature through plots, to investigate how these parameters affect each other and observe the similarities and differences between the behaviour of the two blocks. Graphs, comparing line 4 and 8 will be presented as an example of the behavior of each block, while more graphs of other lines can be found in the appendix B.

5.1. Existing data

For this study data for a period of approximately 7 years are considered. These data include average daily measurements of the following parameters for each line:

- Turbidity (FTU), measured at the end of the outlet of the lamella settlers.
- Water Temperature (°C), measured when water arrives at the treatment plant.
- Flow (l/s) measured at the inlet of the flocculation basin.
- Coagulant dosage (g/m^3).

It is known that since June 2017 a low dosage of polymer has being added in the flocculation basins in lines 1 and 2 and since May 2018 it is added to all lines of block 1.Moreover drawings of the basins of both blocks were available, based on which the design of the basins were studied.

5.2. Collection of additional data

In order to get a better understanding of the flow and the sedimentation process in the basins some additional data were collected through measurements regarding settleability and concentration of suspended solids, and turbidity along the basin. However it should be noted that these measurements were made after October 2018, thus the polymer is used in block 1, contributing to a better performance of the block.

5.2.1. Concentration of suspended solids

To estimate the concentration of suspended solids in the water that enters the lamella settlers, a well-mixed 500ml sample of water was filtered under vacuum through a glass fiber filter disk. Before filtering the sample, the dry weight of each filter was measured. During the filtration process, the solids present in the water are kept on the filter and the dry weight of the filter is measured again. The suspended solids' concentration is calculated as the difference between these two weight values (Table 5.1). The concentration of suspended matter at outlet of flocculation seems to be similar between all lines. This similarity is expected as the analogy of flow rate and dosage of coagulant was approximately the same for the 2 blocks when the samples were taken.

Table 5.5.1: Results from filter tests.

Line	W_{filter} (g)	$W_{(filter+SS)}$ (g)	Vol (ml)	Δw (g/500 ml)	C (g/l)
1	0.1318	0.1448	500	0.0130	0.0260
2	0.1332	0.1468	500	0.0136	0.0272
3	0.1295	0.1423	500	0.0128	0.0256
4	0.1301	0.1431	500	0.0130	0.0260
5	0.132	0.1451	500	0.0131	0.0262
6	0.128	0.1412	500	0.0132	0.0264
7	0.1307	0.1435	500	0.0128	0.0256
8	0.1301	0.1432	500	0.0131	0.0262

5.2.2. Sedimentation tests

The separation of suspended solids from the water is accomplished through flocculation and sedimentation. The particles present in the water are forming flocks with the coagulant (ferric chloride) in the flocculation basin and at the end of it, just before the water enters the sedimentation basin, the flocs are well-formed and ready to settle. Sedimentation tests were conducted several times on one liter samples, by placing the sample in a wide cylinder (Diameter, D =145 mm and height of the water level, H = 85 mm), stirring it and measure the time (t), for the flocs to settle. Further the settling velocity of the flocs could be estimated as H/t , where H is the distance the particle traveled until the bottom of the cylinder, and t the time it took the particle to travel through that distance (table 5.2). The samples were taken from the end of the flocculation basins (before the inlet of the lamella settlers).

Table 5.2: Time needed for samples of 1 litter to settle in a cylindrical tube of diameter *D* =14.5 cm and height *H* = 8.5 cm.

Line	time (s)	settling velocity (mm/s)
1	261	0.326
2	249	0.341
3	274	0.310
4	375	0.227
5	307	0.277
6	315	0.270
7	300	0.283
8	267	0.318

An important problem that occurred during this procedure was that the flocs were breaking while the samples were taken. Another factor contributing to the flocs' deformation was the temperature difference between the location of the basins and the laboratory. Temperature affects not only water viscosity but also the chemistry and rate of coagulation process (Fitzpatrick et al., 2004). When a sample was placed in the cylinder the flocs were already destroyed and a very small percentage of them were able to settle. By stirring the sample five to six times the flocs were recreated and the settling time was finally measured.

5.2.3. Turbidity measurements

Turbidity is the haziness of a fluid caused by suspended solids that are usually invisible to the naked eye and it is an important factor regarding the quality of water. As water transparency is crucial for the transmittance of UV-light through the water, the efficiency of UV-disinfection depends on turbidity (Cantwell & Hofmann, 2011), and it is often measured prior to disinfection in the treatment process (Farrell et al., 2018). Turbidity is determined by measuring the degree to which light is scattered by the suspended particles in the water and the measurement depends on the wavelength of the light and the angle at which the detector is positioned.

In order to observe if the turbidity varies along the lamella settlers, turbidity measurements were conducted in several locations along the basins. Samples were taken from the end of the flocculation basins and from the outlet channel at the beginning, the middle and the end of the lamella settlers for all lines. For lines 1 and 4 and 5-8 it was possible to take samples from the lamella settlers and in the middle point between the beginning and the middle, and the middle and the ending of the settlers (figure 5.1). For each sample several turbidity measurements were conducted.

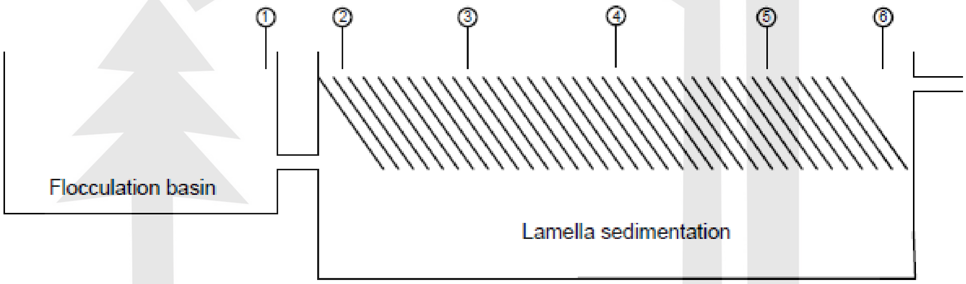


Figure 5.1: Scheme of the locations where samples were taken to conduct turbidity measurement, (1) at the end of the flocculation basins, (2) the beginning of the basin $\chi=0$, (3) $\chi=$ ¼ of the basin's length, (4) middle of the basin ($\chi=$ ½ of the basin's length), (5) $\chi=$ ¾ of the basin's length and (6) the end of the basin $\chi=$ basin's length.

Turbidity was measured with the instrument Turb 555IR in Formazine Nephelometric Units (FNU), meaning that the samples were measured in a 90 degrees angle with an infrared light source according to the ISO 7027 method (table 5.3).

Table 5.3: Measured turbidity in different locations, as described in figure 5.1, for each line.

	Turbidity (FNU)					
Line	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
1	7.60	0.78	0.80	0.50	0.46	0.47
	7.30	0.66	0.87	0.50	0.45	0.45
2	6.90	0.55	-	0.51	-	0.44
	7.60	0.54	-	0.50	-	0.45
3	7.80	0.60	-	1.55	-	0.48
	7.14	0.55	-	1.60	-	0.50
4	8.00	0.80	0.70	0.70	0.44	0.44
	7.80	0.70	0.65	0.72	0.55	0.45
5	3.30	0.49	0.46	0.50	0.38	0.36
	3.10	0.50	0.49	0.50	0.37	0.35
6	2.80	0.53	0.46	0.48	0.36	0.40
	2.00	0.49	0.51	0.45	0.37	0.37
7	5.00	0.55	0.50	0.45	0.59	0.50
	4.30	0.56	0.48	0.47	0.46	0.60
8	7.40	0.80	0.60	0.55	0.47	0.50
	6.40	0.82	0.62	0.56	0.48	0.50

Due to the fact that the determination of turbidity is not often precise, turbidity tests were also conducted in the water that the on-line instrument of the treatment plant measures. The aim of these measurements is to estimate the difference between the on-line instruments and Turb555IR results. It can be seen on table 3, that the difference between the 2 measurement instruments does not exceed ± 0.9 % FNU (table 5.4). The location of these measurements is the outlet of the lamella settlers.

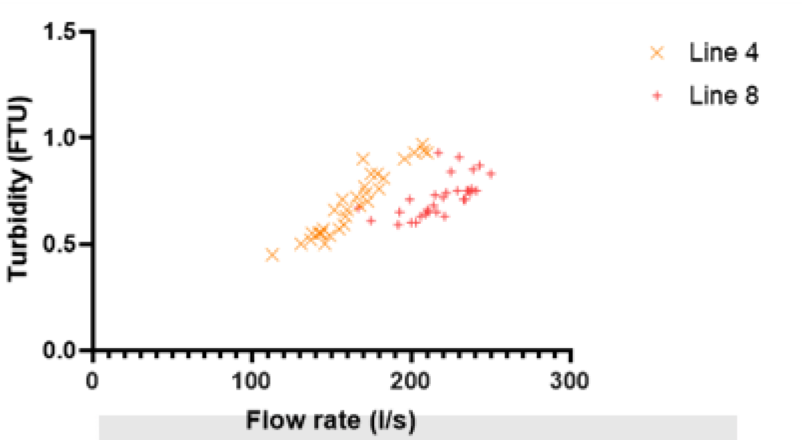
Table 5.4: Turbidity values from the on-line instrument and measured by Turb555IR at the same location.

Line	Online instrument (FNU)	Measurement (FNU)
1	0.43	0.48
2	0.43	0.44
3	0.36	0.38
4	0.43	0.43
5	0.68	0.61
6	0.59	0.5
7	0.64	0.56
8	0.67	0.60

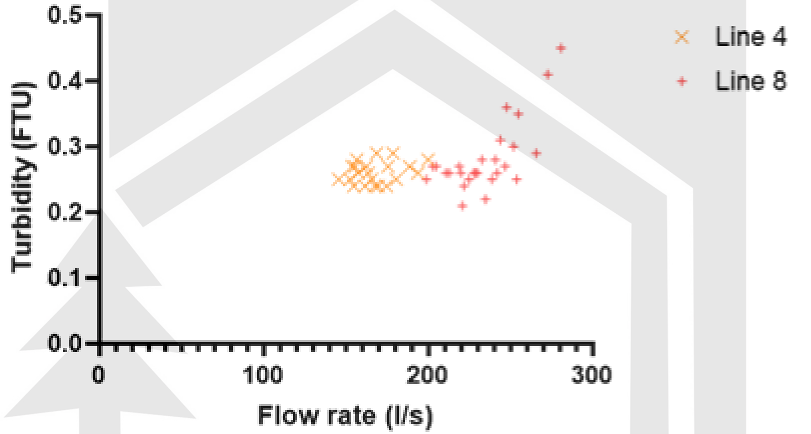
5.3. Data analysis

The existing data, given by the treatment plant, are analyzed though plots to observe the relationship between turbidity and flow as well as turbidity and temperature in each block. As the two blocks have a different design, data for one line from each block are plotted and the two lines are compared with each other, representing the design of their block. Because line 3 had been modified in the past it was excluded from the plots, as it cannot represent the actual design of block 1. Although it is of interest to investigate the modified design of line 3, its performance, as seen through this data, remains similar to the rest of the lines in block 1 so it is not compared to the other designs in this chapter.

Turbidity and flow data are plotted, using the daily data from all years given, except the dates when polymer is used, and under the same temperature and coagulant dosage to eliminate the effects of these parameters on the turbidity. As temperature is an important factor for turbidity, turbidity-flow graphs are plotted for a low and a high temperature. In both cases, lines in block 2 can have the same turbidity as lines in block 1 for a larger flow rate (figure 5.2). This indicates that there is a problem with capacity in block 1 as if for higher flow rates, turbidity would increase significantly.



(a)



(b)

Figure 5.2: Variation of turbidity with flow rate for (a) Temperature T = 3.5 °C and (b) Temperature T = 17.0°C.

From the graph above (figure 5.2), it can be observed that under a low temperature of 3.5 °C, line 4 has the same turbidity as line 8 when the flow rate in line 4, Q_4 is approximately 25 % less than the one in line 8, Q_8. When the flow rate is the same line 4 has 25 to 30 % higher turbidity than line 8, while under 17 °C the problem remains but seems to be less severe. In this case, the two lines have the same turbidity when Q_4 is around 20 to 25 % less than Q_8, while line 4 has similar values of turbidity this time.

When comparing the two graphs, the effect of temperature on turbidity can also be observed as turbidity values in both lines fall significantly when the temperature rise. The differences in values due to temperature are summarized on the table 5.5 below.

Table 5.5: Minimum and maximum values of turbidity (FTU) for temperatures 3.5 and 17 °C.

	Line 4		Line 8	
T (°C)	Q (l/s)	FTU	Q (l/s)	FTU
3,5	113	0,45	192	0,59
	207	0,97	217	0,93
17	155	0,24	221	0,21
	179	0,29	281	0,45

If instead of using the data from all seven years, the same plots are made per year the result is similar. As an example, year 2014 is presented below (figure 5.3), where line 4 has the same turbidity as line 8 when Q_4 is approximately 18-23 % less than Q_8, under a temperature of 3.5 °C .On the other hand, during a high temperature of 19.5°C, line 4 is having lower turbidity than line 8 for a lower flow.

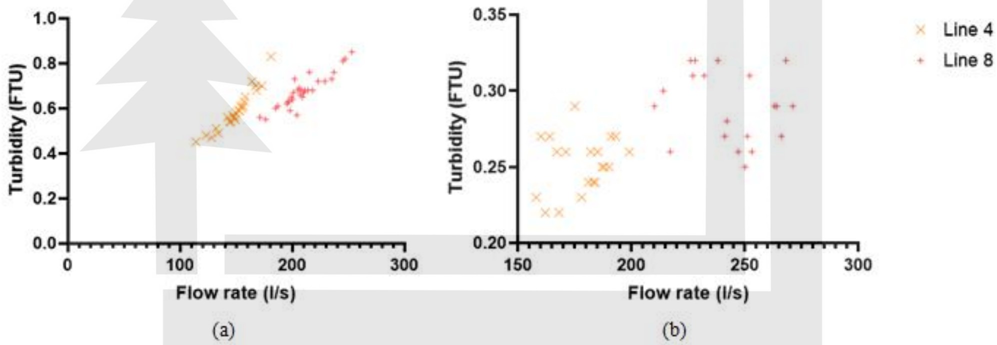


Figure 5.3: Variation of turbidity with flow rate in 2014, when (a) T= 3.5 °C and (b) T=19.5 °C.

To observe how similar or different the turbidity values are in the two lines when Q_4 is up to a certain percentage lower than Q_8, the graphs below were made. In the first case (figure 5.4(a)), when Q_4 is 18% less than Q_8, turbidity in line 4 is not only similar to the one in line 8, but in some temperatures it is larger. Other cases where Q_4 is 24 and even 32 % less than Q_8 (figure 5.4(b) and 5.4(c)) were also investigated, showing that turbidity values are significantly close.

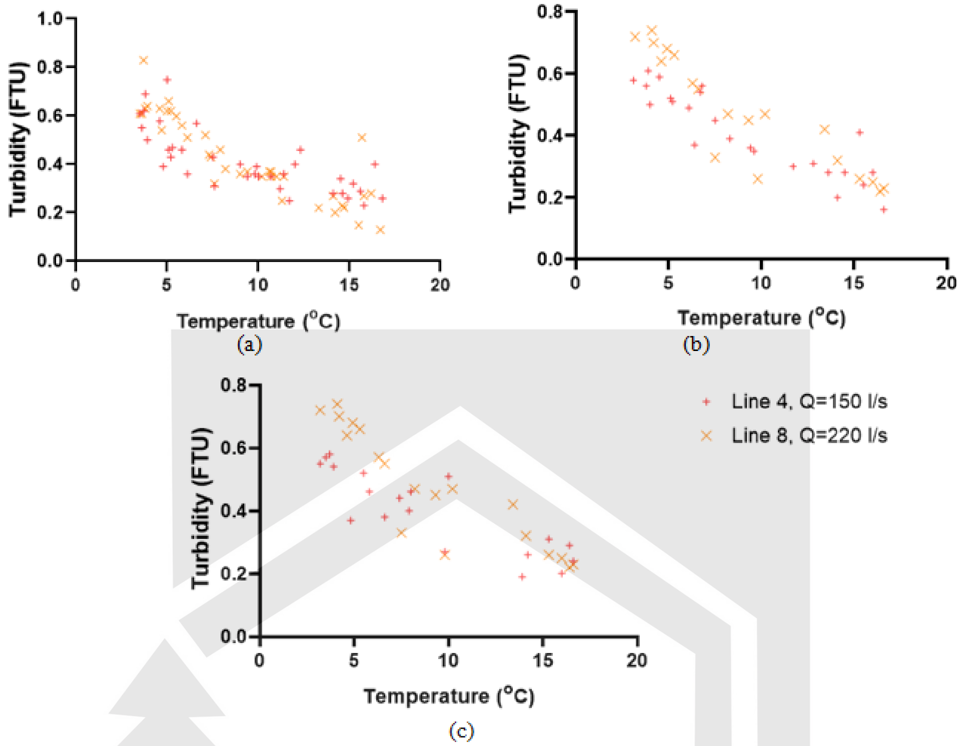
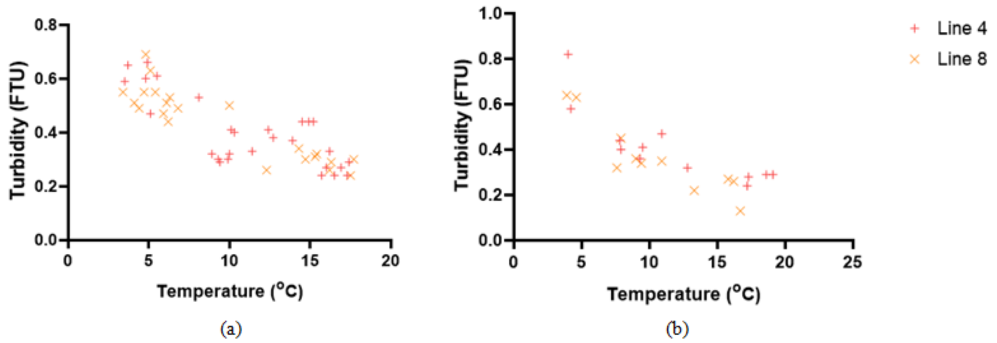


Figure 5.4: Comparison of the variation of turbidity with temperature in lines 4 and 8 when they have a different flow rate; (a) $Q_4 = 0.82Q_8$, (b) $Q_4 = 0.76Q_8$ and (c) $Q_4 = 0.66Q_8$.

Further, the variation of turbidity over temperature in lines 4 and 8 when the lines have the same flow rate was investigated. It is not often that the two blocks have the same flow rate as lines 5-8 usually process a flow higher than the average maximum flow in lines 1-4. However, there were enough occasions where a flow around 190 l/s was common and examples when both lines have the same flow are presented in figure 5.5 below.



(a) (b)

Figure 5.5: Comparison of the variation of turbidity with temperature in lines 4 and 8 when they have the same flow rate; (a) Q_4=Q_8=180 l/s and (b) Q_4=Q_8 =200 l/s.

From the above analysis of all the available data prior to the addition of a polymer, the insufficient performance of block 1 can be confirmed as it reaches high turbidity values for a flow rate less than 200 l/s per line, while the maxim designed flow rate is 300 l/s. If block 2 is taken as an example of the turbidity values that should be expected under a flow rate of 200 l/s or higher, block 1 reach these values already for approximately 20 % less flow than block 2. In general, block 1, has this behavior under low and high temperatures, but as during high temperatures, turbidity is already low under a high flow rate, the problem is consider more sever during low temperatures where there is a chance that block 1 would reach the maximum allowed value.

On the other hand, the additional data reflect the system with the use of a polymer. Block 1 and 2 have similar values of suspended solids concentration, settling velocity of the flocs and turbidity. The existing data on the dates that the measurements were conducted confirms that block 1 can now process higher flow rates with satisfactory turbidity values similarly to block 2.

6. Hydraulic model of the lamella sedimentation

In this chapter a hydraulic model will be developed to describe the system of the lamella settlers in each block in order to evaluate and compare these designs. An important limitation, when creating the model was that there are some uncertainties about the geometry of the system and especially the inlet structures. On the other hand, it was not possible to conduct any measurements, within the lamella settlers, besides the outlet flume, and factors such as flow rate and consequently velocity are estimated based on the flow rate measured before lamella settlers for each line and the assumption that the flow in each line is equally distributed between the lamella rows and lamella plates.

6.1. Water flow and removal rate

The lamella settlers in Ringsjö water treatment plant operate under counter-current flow pattern, i.e. between two lamellas, the water is moving upwards while the sludge is moving downwards on a lamella plate. However, the inlet configuration of the settlers differs significantly between block 1 and block 2 and as a result the flow path that the water follows in each design is different. Block 1 follows a design where the water is distributed into channels in order to be further distributed between the lamella plates while block 2 follows a much simpler design where the water just flows from the flocculation basin into the lamella settlers.

In detail in block 1 the water exits the flocculation basin from a rectangular opening in the basins hole and the water is equally distributed into the inlet channels of the settler. Up next the water is assumed to be equally distributed between the lamella plates, from the opening in the bottom of the inlet channel and flow upwards (figure 6.1), so that the sludge will slide onto the lamella plate and settle at the settle zone in the bottom of the basin. The water reaching the top of the lamella plates is flowing through a triangular weir into the outlet channel.

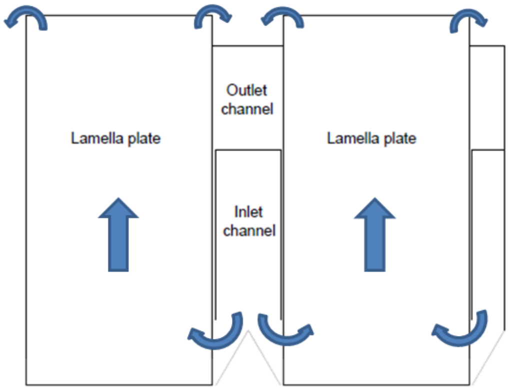


Figure 6.1: A sketch of the water flow path in the lamella sedimentation basins in block 1.

As seen in figure 6.2(a), in block 2 water flows above the flocculation basin's wall and continue its path into the lamella settler by flowing under the lamella packs. The water then flows upwards in a lamella plate from underneath it and as in block one the water flows out of the lamella plates and into the outlet channel through triangular weirs (figure 6.2(b)).

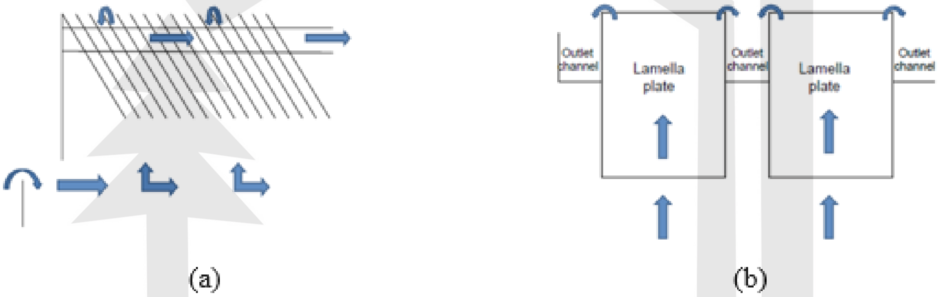


Figure 6.2: Sketches showing the water flow path in the lamella sedimentation basins in block 2.

Due to this different flow path, the hydraulic losses that occur in each system are also different. Besides the hydraulic loss between 2 plates, which is common in the 2 systems, in block 1, losses occur also when the water enters the inlet channel, along the inlet channel and when the water flows from the inlet channel into the space between two lamella plates.. There is a considerable degree of uncertainty, regarding the losses in some parts of the system, as the value of the loss coefficient *K* is assumed to be 1, so that the losses could be slightly overestimated, and the exact dimension of some parts of the system is uncertain. However the hydraulic losses even for the maximum designed flow (300 l/s per line) can be considered negligible as they are in magnitudes of μm, besides the losses due to friction in the inlet channel which are in magnitude of mm (Appendix, C).

An important factor that reflects the performance of the system is its removal efficiency. The removal rate of each line was estimated based on the advection-diffusion model as described in literature review by using the settling velocity of the SS, w, that was estimated from the sedimentation tests and the flow rate, *Q*, that was measured when the measurements were conducted (table 6.1). Though lines 1-3, three out of the four lines in block 1, appear to have theoretical removal efficiency larger than 97%, it should be taken into consideration that polymers were used in the purification process for lines 1 to 4 at that time, which contributed to a large removal rate.

Table 6.1: The removal rate, *β*, per line, estimated by the advection diffusion equation for a measured settling velocity *w*.

Line	*w* (mm/s)	*β* (%)
1	0.326	97.9
2	0.341	98.3
3	0.310	97.4
4	0.227	92.1
5	0.277	91.0
6	0.270	90.4
7	0.830	99.9
8	0.318	94.1

On the other hand, the removal rate of each line can be estimated based on the Hazen's model (Appendix D). Hazen's equation of removal rate includes not only the settling velocity w but also the critical velocity w_c , which is calculated to be 0.1 mm/s for lines 1-4 and 0.12 mm/s for lines 5-8. By inserting these values into equation 5, removal rate value for each line,*β* is larger than 1, meaning that the concentration of suspension solids is completely removed.

6.2. Model validation and Sensitivity analysis

An important step after model development is model validation, where the accuracy of the model can be estimated. For this project real system measurements are used to demonstrate if the model can be considered a reasonable representation of the actual system. The model, is validated by estimating the removal rate of each line based on measurements of the system, and compare it with the output of the model.

However measurements of suspended solids before and after the lamella sedimentations were unavailable and an estimation of the turbidity removal rate will be used as an indicator of the removal rate of the basins (table 6.2).

Table 6.2: Removal rate of each line based on the turbidity removal according to turbidity measurements of the water entering and leaving the lamella basins.

Line	FNU before L.S	FNU after L.S	Removal rate (%)
1	7.45	0.46	93.8
2	7.25	0.45	93.8
3	7.47	0.49	93.4
4	7.90	0.45	94.3
5	3.20	0.36	88.7
6	2.40	0.38	84.2
7	4.65	0.55	88.2
8	6.90	0.50	92.7

The ability of lamella settlers to remove turbidity appears to be more satisfactory in block 1 than in block 2, similarly to the removal rate, β, calculated based on advection-diffusion equation. An important consideration when comparing these results is that the flow rate value could differ in each case. Lines 1-3 had the exact flow rate in both cases, and their turbidity removal is approximately 4-4.5% less. Assuming that turbidity removal rate is comparable to suspended solids removal rate, calculate with the advection diffusion equation, the model appears to have a low degree of uncertainty. Furthermore, measurements of the water level at the weirs, shows that the hydraulic losses of the system are negligible, as the water lever was the same along the sedimentation basin.

To analyze the effect of the different variables in the model sensitivity analysis was performed. The importance of variables such as flow rate, lamella plate size, inclination angle and inlet channel geometry for the system is tested by changing one variable at the time and observe how the output result changes. It is already known that flow rate and lamella plate characteristics are important parameters regarding the performance of lamella sedimentation. Through sensitivity analysis, the degree up to which these parameters affect the system can be estimated (Table 6.3). It can be observed that when adding 50 l/s to the flow rate (for flow rate $Q \geq 200$ l/s) the removal rate, β, is decreasing approximately 5 % , while an increase of the lamella length and angle of inclination can have a positive effect on the removal rate.

Table 6.3: The Removal rate, β, is recalculated by changing one parameter at a time in order to observe the significance of each parameter. As an example the removal rate of line 1 was used.

	Flow rate (l/s)	Length of lammela (m)	Angle of inclination (degrees)	β (%)
Initial model	**165**	**2,55**	**55**	**97,95**
Changing the flow rate	100	2,55	55	99,94
	150	2,55	55	98,74
	200	2,55	55	95,45
	250	2,55	55	90,83
	300	2,55	55	85,94
	350	2,55	55	80,68
	400	2,55	55	75,78
Changing lamella plate length	165	2,2	55	96,51
	165	2,4	55	97,43
	165	2,6	55	98,1
	165	2,8	55	98,6
	165	3	55	98,97
changing angle of incilantion	165	2,55	50	98,64
	165	2,55	60	96,76

7. Possible future design of the lamella settler

In this chapter, other possible designs of the lamella sedimentation that could replace the current settlers of block 1 are investigated and evaluated. Since the settlers of block 2 are having a satisfactory performance, one possible scenario would be to reconstruct the lamella settlers based on the design of block 2. However, as this design requires more space, it is of interest to evaluate if it would be possible to increase the capacity of the settlers in block 1, by applying some modifications in the current design, and avoid their reconstruction. The type and the location of modifications needed in the system depend on the cause of the problem. If the problem appears due to disturbances in the flow conditions, the feed of water to the lamella area can play an important role in the solution.

7.1. Modifications in the inlet channel

In the current system the water flow enters the lamella with an angle to the plate, which might disturb the laminar flow conditions. By moving the bottom of the channel downwards or even removing it completely, the water will be able to enter the lamella area from underneath the plates and consequently flow parallel to them and make use of bottom centimeters of the lamella length for sedimentation (figure 7.1). Moreover, this would slightly increase the time that the mixed liquid requires to reach the lamella plate, allowing the flocs to grow even more until they finally reach the lamella plate.

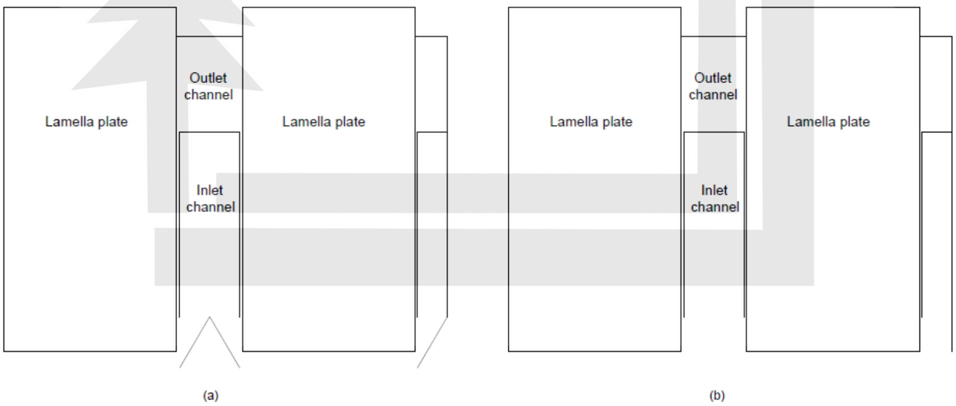


Figure 7.1: Possible future modifications of the inlet channel to increase capacity. a) The bottom of the inlet channel has moved downwards and b) the bottom of the channel has been removed.

A similar design was implemented in line 3 in the past, but the line did not show any improvement. In the settlers of line 3, the bottom of the channel was removed in a small part of the channel, close to the entrance. If the capacity of the basins is decreased due to turbulence occurring as the water takes a turn when fed to the lamellas from the channel, maybe small changes in the feed as the above could increase the capacity. However, if that is the case, the changes in line 3 would probably make a difference in line 3, even if the maximum capacity wasn't reached.

7.2. Co-current lamella settler

Another possible modification of the current system is to change the flow pattern from counter-current to co-current. Counter-current is usually preferred due to its simple and cost-effective design, but literature suggests that co-current flow is more suitable for the removal of light sludge. In the co-current flow pattern, in addition to the gravitational force, a drag force acts also to remove the sludge (Forsell and Hedström, 1975), so this system can be in favor of floc settling. In order to change the lamella settler to co-current, major changes need to be done in the basin as both the inlet and outlet will have to be reconstructed, so that the feed to the plates will now be in the top of the basin and the water flow will, in that case, flow from the top of the plate downwards and then upwards (figure 7.2).

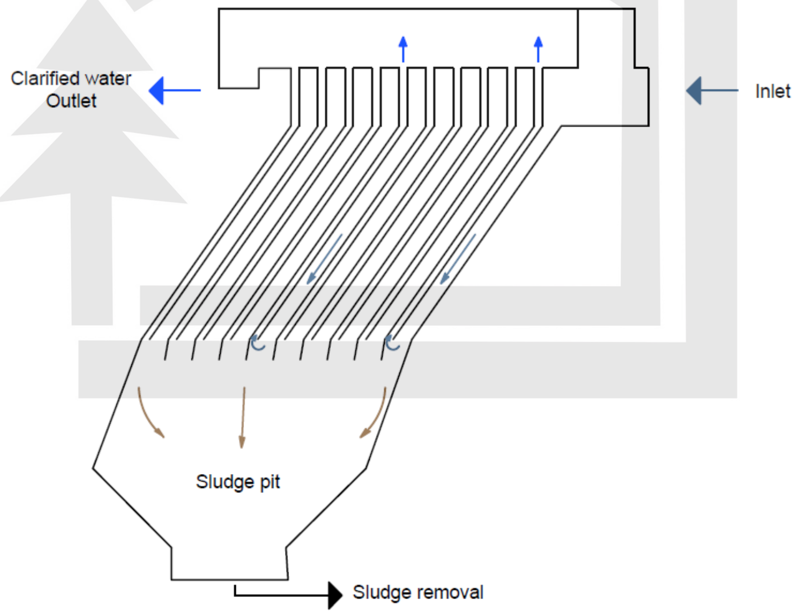


Figure 7.2: Scheme of a typical co-current sedimentation settler.

7.3. Reconstruction of the current basins

If the basins are to be reconstructed, the two designs could be combined. In that case, a new sedimentation settler can be constructed with an inlet similar to block 1 but with a pyramid shape so that it maintains a smaller footprint than a rectangular shape basin (figure 7.3). The water will flow into the settler from an opening in the wall of the basin and flow underneath the lamella packs, where it can equally be distributed to lamella plates. Besides the inlet structure the pyramid shape of the original basins will need to be wider to secure the stability of the settlers, so the walls of the settler will have to be reconstructed and the bottom of it wider.

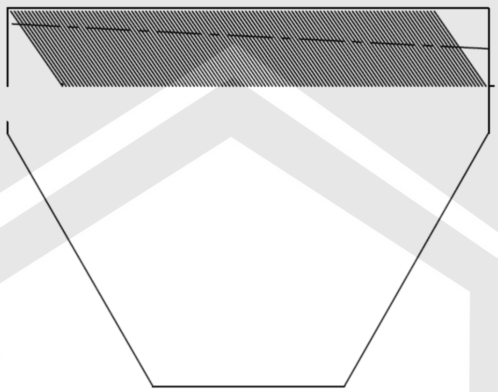


Figure 7.3: A design of lamella settler that combines the advantages of each design, i.e., a simple inlet structure and a pyramid shape part to decrease the volume of the settler.

Furthermore, the space between flocculation and sedimentation basins could be used to extend the volume of flocculation basins, which could contribute to a higher detention time. It should be mentioned that, even if the lamella settlers were to be reconstructed according to the design in block 2, the flocculation basins would also need to be reconstructed, as it is not guaranteed that this design will be as efficient as it is now, if the flocculation's residence time is as the one in block 1.

7.4. Modifications in cogulation/flocculation

As a temporary solution, a polymer is added in block 1, contributing to the creation of large flocs, and thus increasing their settleability. Since the addition of polymer increased the capacity of the lamella settlers, modifications in the coagulation/flocculation could be considered as an alternative. Expanding the flocculation basins of block 1 would increase its residence time, leading to the formation of larger flocs, strong enough to settle without the aid of polymer, as in block 2, which is performing well while having approximately 20 % larger flocculation volume. However, this is probably not feasible due to space limitations and another alternative could be to investigate if another coagulant could develop stronger flocs in the current basins.

8. Discussion

In this study, the different designs of the lamella settlers were analysed and compared, as the reason behind the poor capacity of block 1 could be related to their differences. The behaviour of only one line from each block, lines 4 and 8, were observed and compared through a data analysis, based on the assumption that the lines of each block have similar performance. To ensure that it would not make a difference if other lines were chosen, data related to other lines were also plotted, giving similar results, as the comparison between lines 4 and 8 (appendix B).

Data analysis confirms that there is an important difference between the capacities of the two blocks when no polymers are added in the process, as only line 8 seems to respond well under a high flow rate. More specifically, the two lines have the same turbidity in the sedimentation settlers when line 4 processes approximately 80% of line 8's flow rate. Through the graphs it is observed that the function between turbidity and flow rate is not linear, but as turbidity values are hard to be estimated with high accuracy, it is not clear if the function is exponential. This is one reason why even though there are cases where block 2 has higher turbidity than block 1, the flow rate in block 1 should not be increased, as even a small increase in the flow rate could result in significant high values of turbidity.

Since polymers were added in block 1, it can reach higher values of flow rate and have a similar turbidity as in block 2. The addition of polymers was a limiting factor when the new measurements were conducted, as the values measured were not reflecting the original performance of lines 1-4, which was of interest. Based on the sedimentation tests, the settling velocity of the flocs was estimated for each line to be used in the calculation of their removal rate, β. As a result, with the polymer, lines 1-4 appear to have an excellent performance. Without the polymer, it can be assumed that these lines would have a lower removal rate, although, how much lower is unknown.

Moreover, the water flow movement in each design of lamella settlers was investigated and the hydraulic losses were estimated, assuming that the flow was equally distributed among the lamella plates. According to literature, lamella sedimentation operates under laminar flow and equally distribution between the plates. If an unequal distribution of the flow occurs in the basins, some parts of it would be overloaded while others would be underloaded, resulting in a poor performance of the settler. If that was the case in block 1, then there would be differences in the water level when the water flows through the weirs to be collected in the outlet flume. Measurements in the water levels along the outlet flume, confirmed the initial assumption as there was no variation in the water level. On the other hand, a small variation of the water level would be an indicator of hydraulic losses in the system, so it was also confirmed that the losses were negligible as the calculations suggested.

Furthermore, possible future designs to increase the capacity of block 1 (without the use of polymers), were presented in this study. Three alternatives are analyzed; modifications in the inlet channel, changing the flow pattern to co-current and finally, reconstruction of the basin, to allow a water movement similar to block 2. Which alternative would efficiently replace the current design, depends on the cause of the problem. When comparing the two designs they differ on volume, residence time and the feed to the lamellas. Block 2 has a larger volume in both flocculation and sedimentation basins and a simple feed to the lamellas compared to block 1.

One speculation about the main cause of the problem could be that while the water is fed to the lamellas with an angle to the plates' direction, besides reducing the lamella's effective length, turbulence might be created which would disturb the laminar conditions. If that was the case, or in some other way the feed was the main problem, modifying the inlet channel so that the water would be fed to the lamella plates from underneath, in a parallel direction to the plates, could be considered as a solution. However, since the addition of a polymer increased the block capacity, it would be reasonable to assume that the differences in the flocculation basins play an important role in the sedimentation capacity.

Before shifting the coagulant to ferric chloride, block 1 was able to process high flow rates for flocs created by aluminium sulphate, even though aluminum flocs can be sensitive to low temperatures. Based on this observation, and the fact that in block 2 there is more space and time available in the flocculation basins for the formation of the flocs, it could be assumed that an important factor to the problem is the ability of block 1's flocculation basins to format strong iron flocs. As, the floc characteristics (without the polymer) were not investigated, the floc condition before the lamellas inlet was unknown.

More knowledge of the floc characteristics is essential when altering or reconstructing the lamella basins. If the flocs are very light, then a co-current flow pattern could be further investigated as a suitable design for the separation step, while if the flocs are breaking during the separation, due to insufficient formation of the flocs, maybe changes that would increase the residence time should be considered.

9. Conclusions and recommendations

This study investigated the different design and performance of the two blocks in Ringsjöverket. Block 1's poor performance was confirmed through data analysis, where it was observed that block 1 has the same turbidity as block 2, while having approximately 20 % lower flow rate. The reasons behind this behavior are not addressed, but by analyzing and comparing the blocks' differences in design and performance, some indications about factors that contribute in the cause of the problem can be found to be further investigated. The lamella settlers of the blocks have major differences in their design, with block 1 having a lower basins' volume and a more complex feed to the lamella plates, which could be relevant to the problem, but not necessarily the main cause. The differences between the flocculation basins should also be considered, as the separation step is highly dependent on the flocculation.

Since the addition of polymer in block 1, its capacity has been increased, leading to the conclusion that the flocs prior to the addition of the polymers might have been small, not dense enough, or simple not well-formed when entering the separation step, resulting in their deformation and a poor settling. Modification in the flocculation and separation step that would increase residence time in the basins, would lead to the formation of large flocs with better settleability, and thus a better performance of block 1.

A detailed study of the floc characteristics would be recommended, as parameters such as floc size, weight, and settling velocity, are significant for the separation step. Future possible designs could be dimensioned and evaluated based on the actual floc characteristics which would successfully increase the capacity of block 1. Moreover, if the cause of the problem is mainly due to flocculation then maybe alterations in the flocculation basins, or even, and in the lamella settlers could be the solution.

10. References

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Appendix A: Drawings of lamella settlers

Below drawings of a line in each block are presented. Though all 8 lines have 8 rows of lamella, lines 1-4 (figure A.1) have 2 basins with 4 lamella rows per line, while lines 5-8 (figure A.2) use one basins per line.

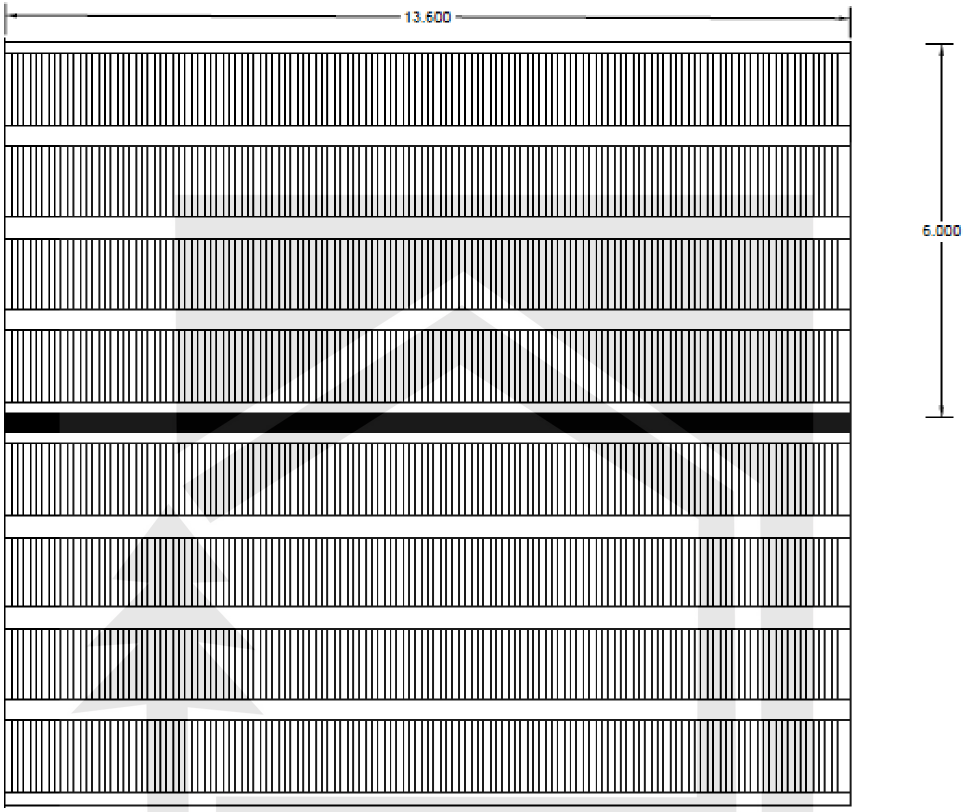

Figure A.1: Drawing of one line in block 1. The line 2 basins with 4 rows of lamella plates each.

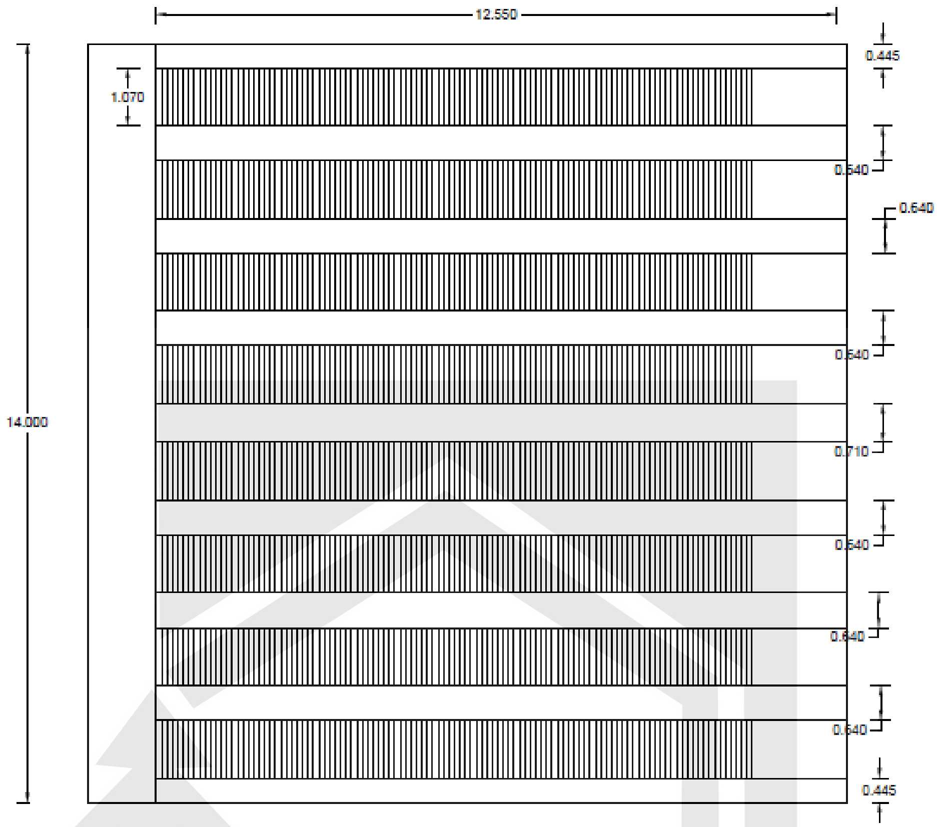

Figure A.2: Drawing of one line in block 2. The line has one basin with 8 rows of lamella pates

Appendix B: Plots of the existing data

Plots of turbidity with flow rate, when polymers were added in block 1.

Below figures B.1, B.2 and B.3 reflect the variation of turbidity in the lamella settlers with flow rate, when a polymer is added in line 4 under a low medium and high temperature respectively. Line 4 seems to have a similar performance as line 8, processing around 200 – 220 l/s without reaching significantly higher turbidity than line 8.

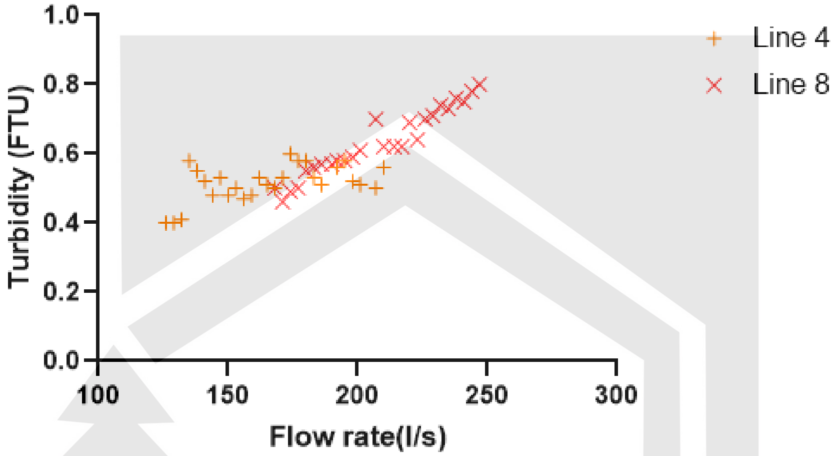

Figure B.1: Variation of turbidity with flow rate , when T= 5 °C, from 1/3/2018 to 30/4/2018.

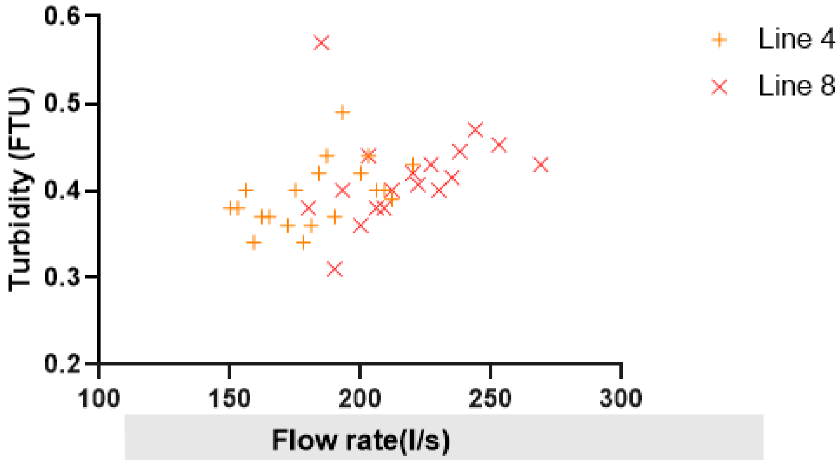

Figure B. 2:Variation of turbidity with flow rate , when T= 10 °C, from 1/3/2018 to 30/4/2018.

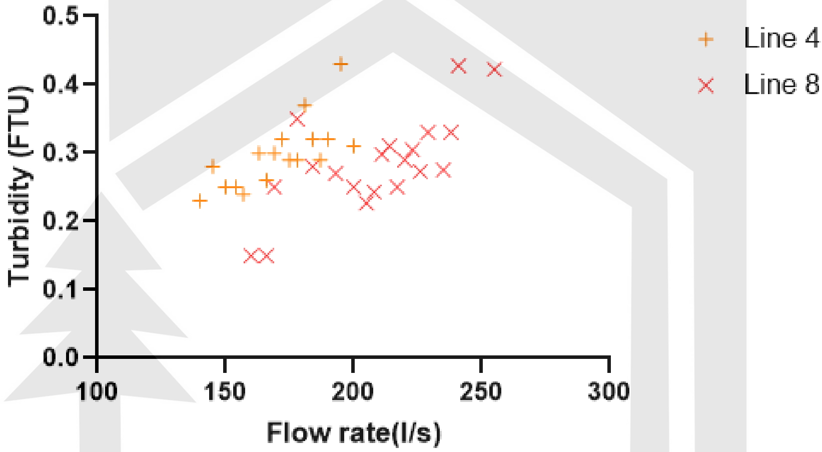

Figure B.3: Variation of turbidity with flow rate, when T= 15 °C, from 1/3/2018 to 30/4/2018.

When comparing the graph in figure B.1 to other graphs comparing line 4 and 8 under a low temperature, prior to the polymer addition (figures B9, B10 etc.), the positive effect of the polymer on the separation step can be observed as without it line 4 would have a turbidity of 0.6 FTU with a flow rate of 155-160 l/s and now for a flow rate of 200 l/s turbidity is approximately 0.5 FTU.

Variation of turbidity with temperature

To observe the effect of temperature on turbidity, all the available data for different lines were plotted. Data when polymer is added to lines 1-4 are not included so that the turbidity of a line of block 1 prior to polymer can be compared to a line of block 2.

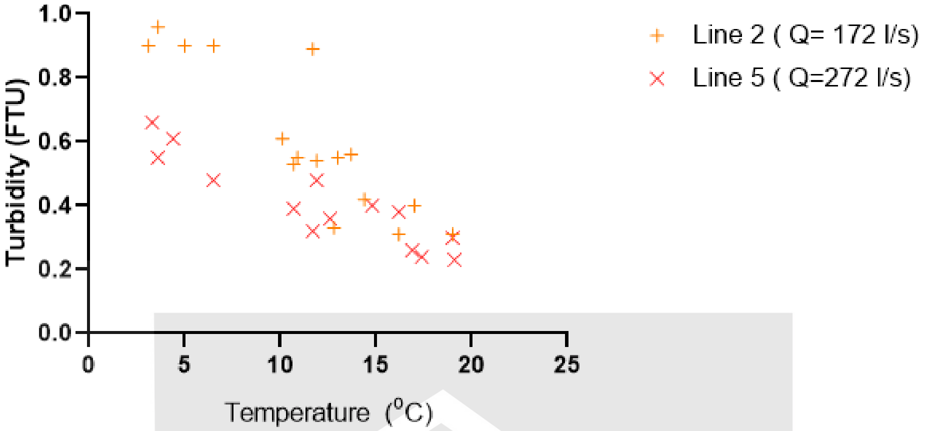

Figure B.4: Variation of turbidity with temperature when the flow rate in line 2 is 50% less than line 5.

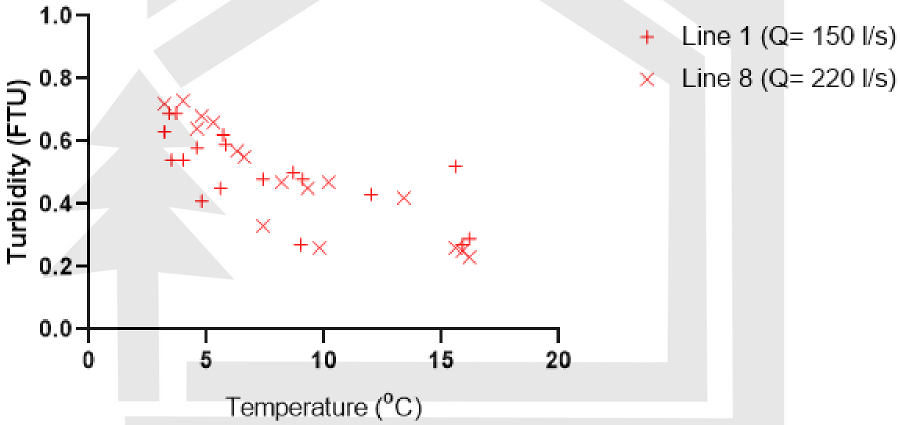

Figure B.5: Variation of turbidity with temperature when the flow rate in line 1 is 32% less than line 8.

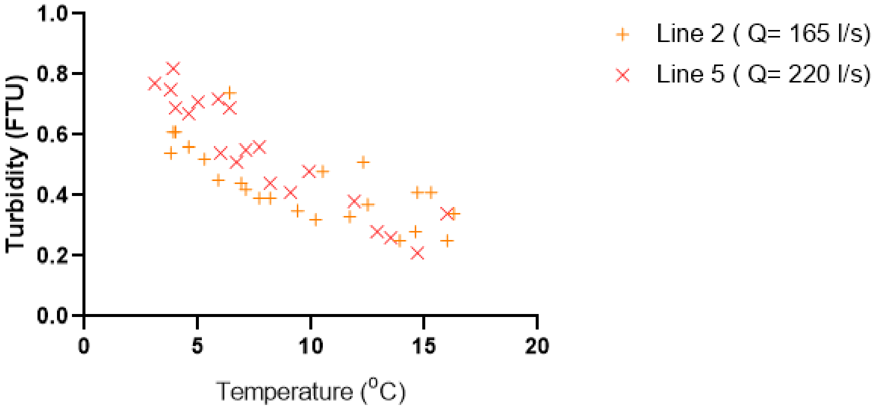

Figure B.6: Variation of turbidity with temperature when the flow rate in line 2 is 25% less than line 5.

Plots of lines 4 and 6 under a warm and a cold period in 2013

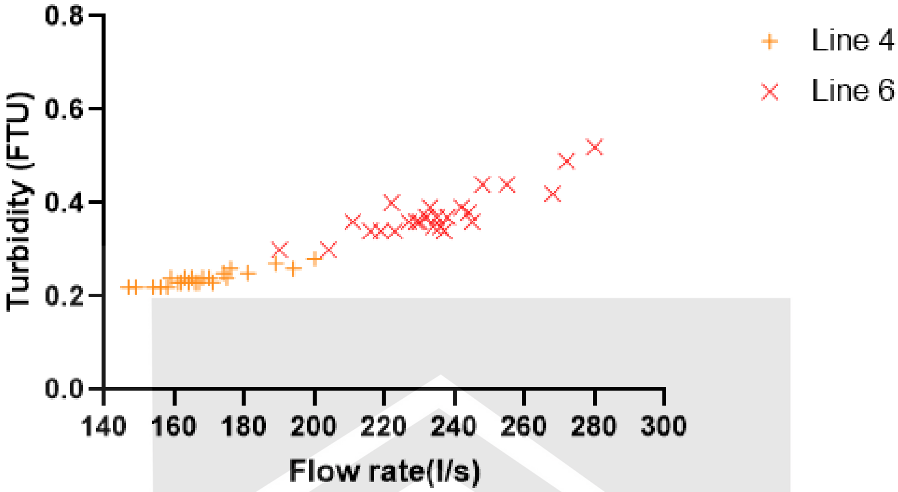

Figure B.7: Variation of turbidity with flow rate, under July 2013.

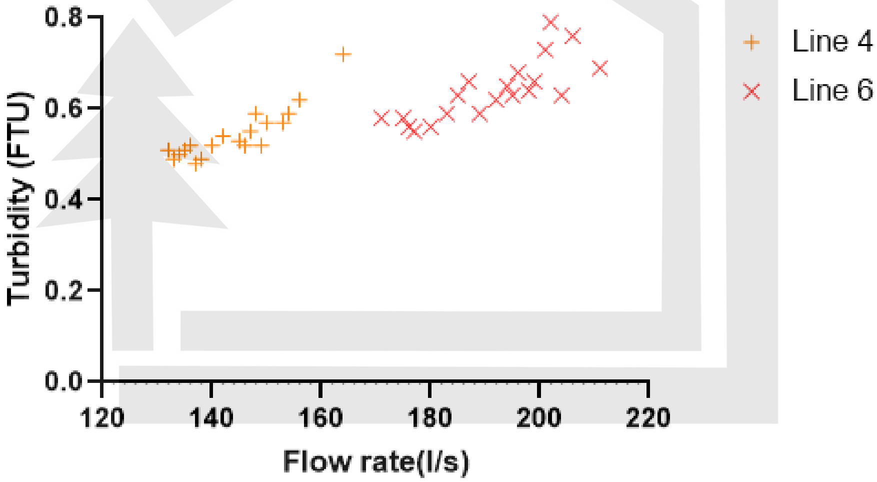

Figure B.8: Variation of turbidity with flow rate, under January 2013.

Plots comparing lines 4 and 8 yearly, under low and high temperature.

In order to compare the performance of lines 4 and 8 using all available data with accuracy and to avoid errors due to average values, the data of each year were plotted separately. Even though data were available from 2011 to 2018, as the data of 2011 did not include all the months of the year, plots were made from 2012 until 2016. The remaining two years were not considered as the polymer was first added in block 1 in 2016.

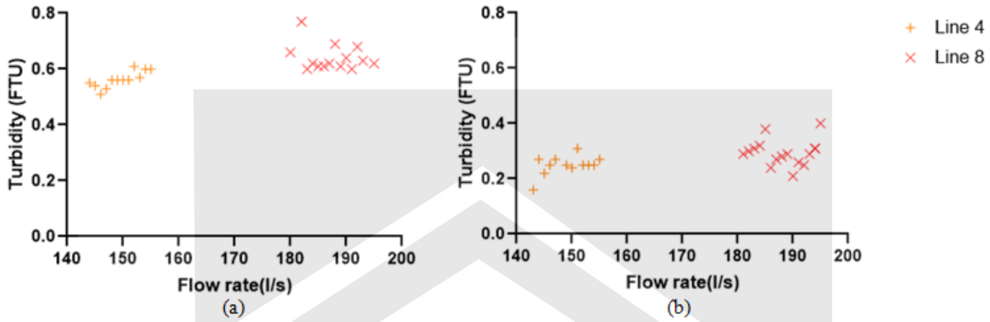

Figure B.9: Variation of turbidity over flow rate in 2012 (a) when T= 3.5 ^{o}C and (b) when T= 17.5 ^{o}C.

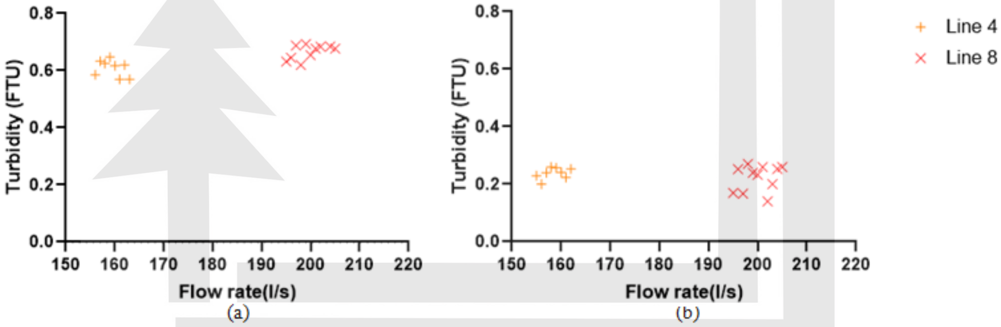

Figure B.10: Variation of turbidity over flow rate in 2013 (a) when T= 3.5 ^{o}C and (b) when T= 17.5 ^{o}C.

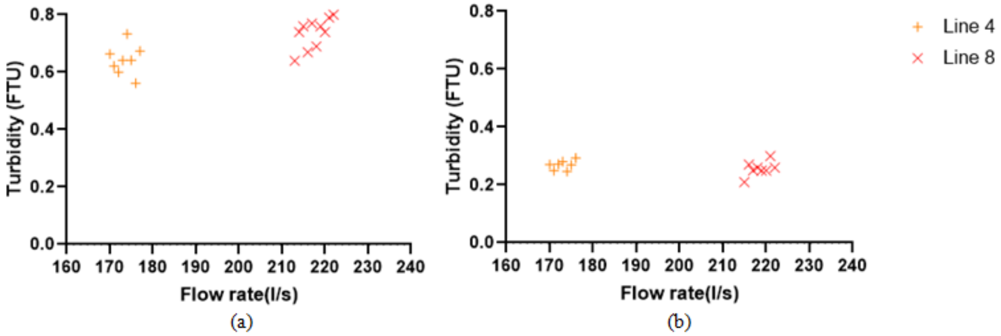

Figure B.11: Variation of turbidity over flow rate in 2015 (a) when T= 3.5 ^{o}C and (b) when T= 17.5 ^{o}C.

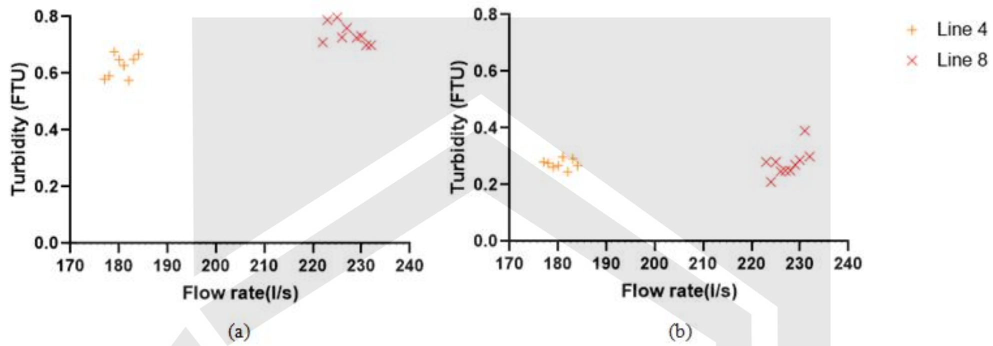

Figure B.12: Variation of turbidity over flow rate in 2016 (a) when T= 3.5 ^{o}C and (b) when T= 17.5 ^{o}C.

Appendix C: Calculations of Energy losses

The energy losses of the system are calculated for the maximum designed flow rate Q_{design} = 0.3 m^3/s per line, and an average water temperature of 10 ^oC. Each line has 8 rows of lamella plates, flow rate in one row, so the flow rate in one row of lamella plates is Q_{row}= 0.3/8 =0.0375 m^3/s.
The calculations are made for a temperature of 10^{o}C, so the kinematic viscosity is ν= 1.139*10^{-6} m^2/s.

Block 1

When following the flow path of water into the system, losses are expected to appear when the water enters and exits the inlet channel, alone the inlet channel and between two lamella plates. Lamella plates in block 1 have a width, *B*, of 1.16 m, a length, *L*, of 2.55 m and the horizontal distance between two plates, *h*, is 0.1 m.

Losses in the the inlet channel

The water into a lamella row is supplied by one channel at its left and one at its right. The channels between two lamella rows are called middle channels and the flow is equally distributed to each lamella row. So in this channels the total flow $Q_1 = Q_{row}$. The channels close to the walls of the basins are supplying only one row and thus they have the design of half the middle channels.

The inlet channels have a slope on their top wall and in the begining of the channel the height of is 1.7 m. The area of the channel *A* can be calculated as the area of the rectangular (0.3x1.7) minus the area of the bottom triangle.

A= (0.3*1.7) – (0.25*0.3/2) =0.51-0.0375 =0.47 m^2

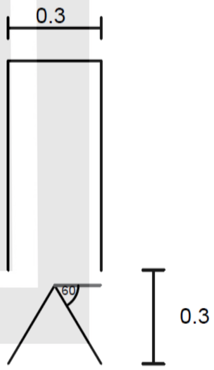

Figure C.1: Cross section of the inlet channel

The velocity of water when it enters the channel can be calculated as:

$$V_1 = \frac{Q_{row}}{A} = \frac{0.0375}{0.47} = 0.097 \text{ m/s}$$

And the energy losses

$$h_{L,1} = K\frac{V^2}{2g} = 1 * \frac{0.097^2}{19.62} = 0.00048 \text{ m}$$

Where K is loss coefficient, usually ranges from 0.25 to 1,
but in this case as the coefficient cannot be predicted with certainty it is assumed to be 1.

The channel's energy loss due to friction can be estimated by the Darcy-Weisbach formula $h_L = f\frac{L}{D}\frac{V^2}{2g}$
where f is the friction coefficient and *D* is the hydraulic perimeter of the channel.

The top of the channel has a slope and consequently the channel cross section is becoming smaller along the channel length. The channel has a height of 1.7 m at the beginning, and 1 m at the end. However, further into the channel when the cross section is smaller than the initial one, an amount of flow was also been distributed, so the velocity will not become significantly higher. Below the losses will be calculated as if the channel had a stable cross section.

The hydraulic diameter, *D*, equals the area of the channel (*A*) devided by its wetted perimeter (*P*). If it is assumed that the area of the top of the channel until the opening on its wall as outlet is the area where water flows then the area A = 0.3 * 1.4 =0.42 m^2 and P= 2*1.4+0.3 =3.10 m

D=0.42/3.10 =0.135 m

The friction coefficient f can be found based on the Reynolds number, Re.
$Re = \frac{VD}{\nu} = \frac{0,097*0,135}{1.139*10^{-6}} = 10000$
From the Moody's diagram, assuming a hydraulic smooth pipe f=0.030
$h_L = 0.03\frac{13.4}{0.135}\frac{0.097^2}{2g} = 0.0014$ m

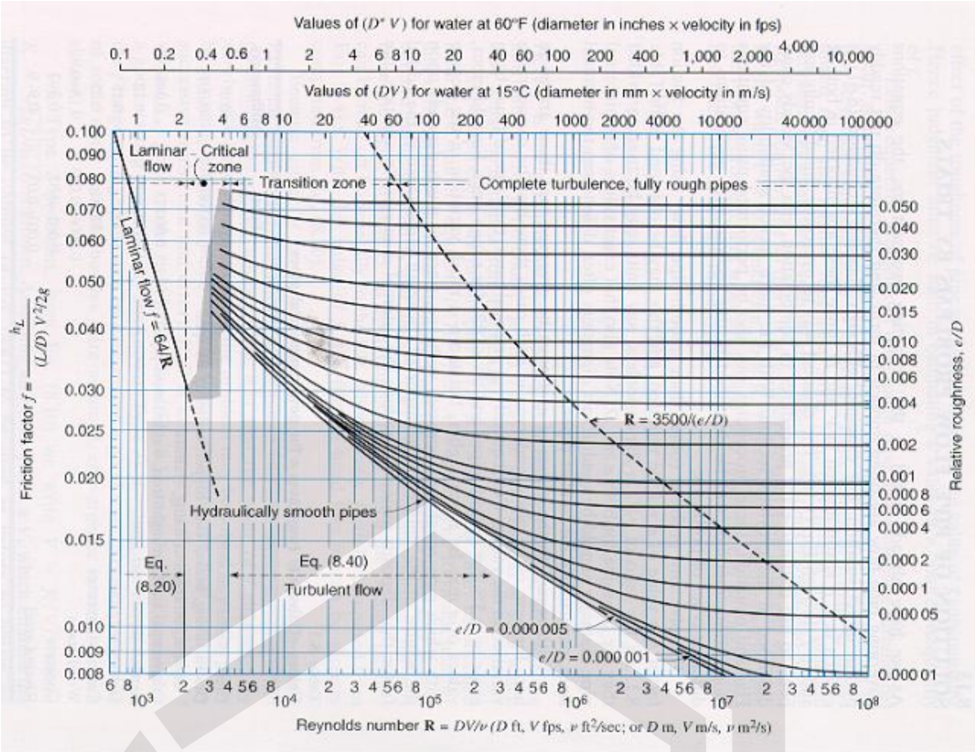

Figure C.2: Moody's diagram

Water exits the inlet channel

There are 120 lamella plates in one row, so the water will be distributed to 119 channels that are formed between 2 plates of lamellas.

The Flow that will be distributed into the lamella row from on channel is $Q_{row}/2 = 0.0187\ m^3/s$.

$Q_2 = \frac{Q_{row}/2}{119} = 0.00016\ m^3/s$

The inlet openings, where the water enters the lamella plates are formed between the opening of the inlet channel (0.3 meters high) and the space between the lamella plates (0.1 m) and thus the area of the inlet holes $A_o = 0.1x0.3 = 0.03\ m^2$

Velocity: $V_2 = \frac{Q_2}{A_o} = \frac{0.00016}{0.03} = 0.0052$ m/s

Energy losses $h_{L,2} = K\frac{V^2}{2g} = 1\frac{0.0052^2}{19.62} = 1.40 * 10^{-6}$ m

Between 2 lamella plates

Flow rate between 2 lamella plates $Q_3 = \frac{Q_{row}}{119} = 0.00032$ m^3/s

Velocity $U = \frac{Q_3}{h*B} = \frac{0.00032}{0.1*1.16}$ =0.0027 m/s

Energy losses : $h_L = \frac{12\mu}{\rho g h} LU = \frac{12\nu}{gh} LU$= 0.11 *10^{-6} m

Block 2

In the lamella settlers of block 2, losses are expected to appear between two lamella plates. A row of lamella plates has 110 plates with a width, *B*, of 1,15 m, a length, *L*, of 2,37 m and the horizontal distance between two plates, *h*, is 0.1 m.

Similarly to block 1 , the hydraulic losses are calculated below.

$Q = \frac{0.0375}{109} = 0.00034$ m^3/s

$U = \frac{0.00034}{0.1*1.15} = 0.0027$ m/s

$h_L = \frac{12\nu}{gh} LU$ =0.14 *10^{-6} m

Appendix D: Lamella sedimentation removal rate

Based on literature, the removal rate of lamella sedimentation can be estimated by the advection-diffusion equation as described in equation below

$$\beta = 1 - \exp\left(- \frac{w \cos \alpha}{V - w \sin \alpha} \frac{L}{h} \right)$$

For a settling velocity w, measured in the sedimentation tests while velocity V can be calculated as

$$V = \frac{Q_{row}}{NBh}$$

Where, Q_{row} (m^3/s) is the flow rate in one row of lamella plates, N is the number of spaces between the lamella plates for one row, B the width of lamella plates
And h the space between 2 plates.

Assuming that the flow is equally distributed, $Q_{row} = Q/8$. The value of Q used in this calculation will be the one that was measured when the sedimentation tests were conducted. Q in lines 1-4 was 165 l/s and in lines 5-8 was 195 l/s so
$Q_{row,1} = Q_{row,2} = Q_{row,3} = Q_{row,4} = 20.62$ l/s
$Q_{row,5} = Q_{row,6} = Q_{row,7} = Q_{row,8} = 24.37$ l/s

The velocity of water, settling velocity and removal rate β are presented below (table D.1).

Table D.1: Removal rate based on the advection-diffusion equation.

Line	V (m/s)	w (m/s)	β (%)
1	0.0014	0.000326	97.9
2	0.0014	0.000341	98.3
3	0.0014	0.000310	97.4
4	0.0014	0.000227	92.1
5	0.0018	0.000277	91.0
6	0.0018	0.000270	90.4
7	0.0018	0.000830	99.9
8	0.0018	0.000318	94.1

On the other hand, lamella sedimentation removal rate can also be estimated based on the Hazen's model, by applying the equation below.

$$\beta = \frac{w}{w_c}\frac{V/w_c - sin\alpha}{V/w_c - w/w_c - sin\alpha}$$

In this case, the critical settling velocity of the flocs, w_c, needs to be calculated for each line as seen below.

Lines 1-4

$w_c = \frac{hV}{Lcos\alpha + hsin\alpha} = \frac{0.1*0.0014}{2.55*cos55+0.1sin55}$ =0.00010 m/s

Lines 4-8

$w_c = \frac{hV}{Lcos\alpha + hsin\alpha} = \frac{0.1*0.0018}{2.37*cos55+0.1sin55}$ =0.00012 m/s

For all 8 lines, β>1 when it is calculated with Hazen's formula, indicating a 100 % removal rate.